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Disclaimer

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Abstract

Stray electrons can arise in positive-ion accelerators for heavy ion fusion or other applications as a result of ionization of ambient gas or gas released from walls due to halo-ion impact, or as a result of secondary- electron emission. We summarize results from several studies undertaken in conjunction with an effort to develop a self-consistent modeling capability: (1) Calculation of the electron cloud produced by electron desorption from computed beam-ion loss, which illustrates the importance of retaining ion reflection at the walls; (2) Simulation of the effect of specified electron cloud distributions on ion beam dynamics; and (3) analysis of an instability associated with a resonance between the beam-envelope "breathing" mode and the electron perturbation. We also report first results from a long-timestep algorithm for electron dynamics, which holds promise for efficient simultaneous solution of electron and ion dynamics. One conclusion from study (2) is that heavy-ion beams are surprisingly robust to electron clouds, compared to *a priori* expectations.

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I.   INTRODUCTION

Heavy-ion fusion (HIF) entails the acceleration of beams of heavy ions to drive inertially confined fusion targets. The main-line approach in the U.S. envisions the use of induction linear accelerators to accelerate multiple beams of ions from an energy of the order of 1 MeV and a current of order of an Ampere per beam, with a pulse duration (time to pass a stationary observer) of 10's of μs, to an energy of the order of few GeV, a current of order of 1 kA/beam, and a duration of $\sim$ 10 ns.

As a positive-charge-particle machine, an HIF accelerator is subject to contamination by stray electrons, which can be electrostatically trapped by the ion beam potential. This is a phenomenon that has been documented in a range of positive-charge-particle accelerators dating back to the 1960's [1]; see Refs. [2] and [3] and references therein. The common concern is that the electron cloud is an uncontrolled negative charge that can alter the ion beam dynamics, possibly leading to beam deflection, increased beam emittance, envelope size, and halo, and also potentially electron-ion instabilities. On the other hand, HIF has a number of distinguishing features that impact both the nature and the modeling of electron clouds.

This report is a brief summary of several studies of the electron-cloud problem for heavy-ion accelerators. The studies are presented in full in a separate paper [4]. That paper also discusses an outline for a self-consistent simulation capability for ion beams in the presence of electron clouds; the present studies exercise ingredients of that capability.

Induction accelerators for heavy-ion fusion possess attributes that signifcantly impact electron-cloud physics. In particular, the combination of high current, large fill factor, long pulse length, and difficulty of wall conditioning imply that the dominant electron source is ionization of neutrals desorbed from walls in current experiments with multi-μs pulses, and in the low-energy end of a driver. For shorter pulse experiments, and at the high-energy end of a driver, electrons produced at or near walls, from electron desorption or from ionization of neutral gas near walls, will dominate. The precise balance depends on the composition and energy distribution of the desorbed neutrals and the pulse length. The same combination of factors listed above implies that self-consistent, simultaneous modeling of electron and ion dynamics is required for a quantitative assessment of electron cloud build-up. We have implemented, and discuss here, elements of such a modeling capability. All simulations are

done with the WARP [5] particle simulation code.

We have undertaken a sequence of simulations to calculate the electron cloud produced by direct electron desorption (due to impact of ions on walls). First, a two-dimensional slice of the ion beam was followed through a 200-quadrupole lattice (with a small misalignment of magnets to exaggerate beam halo scrape-off. From the ensemble of scraped-off ions, a population of scattered ions was calculated from the TRIM surface Monte Carlo code [8], and these were then followed in WARP until their next wall impact. For both the primary and secondary ion impacts, the number and velocity distribution of electrons desorbed was calculated using a fit to the experimental data from Ref. [6]. The resulting electron population is followed in WARP (3D) for 4000 (sub-cyclotron-period) timesteps, enough for several electron bounces. Electrons that are reach the wall are removed from the calculation. The time-integrated electron charge density is formed by incrementally depositing the weighted electron charge density onto the grid. The simulations indicate the importance of including ion scattering at walls. The primary beam ions are lost exclusively where the elliptical beam envelope cross section is closest to the beam pipe. At these locations, the magnetic field lines confine the desorbed electrons to the immediate neighborhood; hence, in particular, there are no electrons in the core of the ion beam. In contrast, scattered ions can reach field wall positions intercepted by field lines that extend deep into the beam interior. Hence simulations retaining scattered ions show finite electron density throughout the beam cross section.

We have undertaken a series of simulations with prescribed (model) electron clouds, which mock up distributions that one might expect from ionization of desorbed neutrals in long pulse accelerators (or neutrals from ambient gas). These simulations are useful for assessing the tolerable level of electron density, and also provide insight into possible instabilities, such as the one discussed below. Once again, the simulation is for a 200-quadrupole (100 lattice-period) system, with parameters similar to compact magnets designed for the High-Current Experiment (HCX) at Lawrence Berkeley National Laboratory [7]. The results indicate that electrons are most detrimental to ion beam quality when the amplitude varies from quadrupole to quadrupole, and a density variation that is resonant with beam breathing modes is considerably more effective than a random variation in producing beam loss and degradation of beam quality. For our model problem with a 100 lattice-period system, a mean 5% electron population, with a 100% resonant modulation, leads to loss of 28%

of the beam. For random variations, even a 10% mean electron density, still with 100% modulation, leads to loss of only about 2% of the beam; doubling the electron density to 20% mean results in a 10% beam loss. Random variations in electron cloud shape or centroid are considerably less effective in degrading beam quality. Resonant variations in electron cloud shape (resonating with the breathing mode) or in centroid position (resonating with centroid oscillations) are detrimental to beam quality, but for the perturbations tested not as detrimental as resonant amplitude variations.

Examination of particle scatter plots show that the nature of the beam degradation is more complex than is captured in line plots of emittance, envelope, and beam current. In particular, the beam halo can acquire a shape quite different from that of the core envelope. We find instances where the halo is circular in cross-section while the core is elliptical, and vice versa. This is not unexpected, as ions in the halo can experience different oscillation frequencies from those in the core. But it implies that fully self-consistent simulations would show a relatively larger role for desorbed electrons than would be otherwise inferred, since there will be significant scrape-off on field lines that penetrate deep into the beam interior. We also find examples where the halo can be concentrated at azimuthal angles as much as 45 degrees removed from the principal core beam ellipse, again on field lines which extend deep into the beam interior.

There are several overall conclusions to be drawn from this study: (1) Heavy-ion beams are actually surprisingly robust to electron clouds. *A priori* there was some expectation that even a few tenths of a percent electrons would be devastating. Even for resonant sinusoidally varying electron clouds with 100% modulation, electron densities in the range of several percent of the beam density are required for substantial beam degradation of a 200-quadrupole system. A constant (from quadrupole to quadrupole) electron density, such as might be caused by ionization of the base pressure of background gas, results in negligible beam loss and envelope growth, and only very minor emittance growth; (2) Electron cloud density modulation resonant with the beam breathing mode is the most dangerous kind of perturbation (at least based on beam loss); (3) elliptical distortions which resonate with beam quadrupole modes have a global effect on beam emittance (related to the effect of a beam mismatch), even though the beam current loss they produce is relatively modest, and (4) electron cloud impact on ion beam propagation is a rich and complex subject, and is not well characterized by the evolution of a few low-order beam moments.

The strong effect of density pertubations resonant with breathing-mode oscillations suggests the possibility of a desorption-driven instability. A simple estimate of the growth rate based on linearized envelope equations suggests a moderate growth rate, comparable to the beam pulse duration for HCX-like parameters. Effects not included in the analysis, such as beam velocity tilt and non-ideal-envelope phenomena (e.g. halo particles having different resonant frequencies than those in the core) should further limit growth.

Finally, Ref. [4] describes a scheme for efficiently simulating electrons which move over a wide range of magnetic-field strengths, by interpolating between a drift-kinetic and full-orbit particle push. The simulation of the electron-desorption-produced electron cloud, described above, was repeated, but with a 25 times larger time step (which now exceeds the electron cyclotron time). The results agree well with ones obtained from with the full-electron-dynamics, small-timestep calculation with a 25 times smaller time step. This scheme enhances the prospects for ion beam simulation with self-consistent electron and ion dynamics.

Acknowledgments

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